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## I. INTRODUCTION

Recent experimental work has concentrated on the study of resultant force and pressure distribution on the stepped barrier designated as Case 5 (W. M. Simpson, Serial 1057, 6 Aug 1953 / J. H. Carr). Case 5 barrier has a plane vertical front face extending the two feet from bottom to still-water surface. Above still-water level are five steps, each of 2.4-in. rise and tread. These dimensions, to a 20:1 scale, represent the prescribed prototype depth of 40 feet and the rise and tread of four feet each.

The separate model barriers for resultant force and for pressure distribution measurements are each cast of aluminum. Vertical ribs at the rear provide rigidity and serve as convenient mounting surfaces.

## II. FORCE MEASUREMENTS

### A. Equipment

The force balance (Interim Report, Dec. 1952 - March 1953) with the associated Case 5 barrier was installed in the two-foot channel in the same manner as were the plane barriers. The one-foot wide active section of the model which transmits wave forces to the balance frames was again located between two passive or dummy sections which were grounded to the channel. The 1/8-inch spaces between active and dummy sections were covered by neoprene tape cemented on either side of the gaps. The tape is made loose enough to provide a minimum restraining force on the balance, yet still prevents "breathing" through the gap.

To determine the relative magnitude of forces acting on the barrier below and above still-water level, two additional tests were performed. The barrier was cut at the still-water line and the bottom part alone served as the active section, the stepped portion being grounded to the dummy sections. Finally, the forces on the stepped portion alone were measured while the lower part was grounded. This experimental determination was of interest because there exists no theory applying directly to stepped barrier profiles.

Figure 1 shows the barrier and balance assembled for measuring forces on the stepped portion only.

## B. Technique

In the plane barrier tests, the wave system incident on the barrier was produced by a procedure of "tuning" the channel (Report E-11.1, October 1953). A stable standing wave was obtained by minute adjustment of the wave machine period in the vicinity of the three wave periods selected for testing. The incident progressive wave height was then assumed to be one-half the standing wave height which was measured at an antinode seaward of the barrier.

With the stepped barrier, however, the appreciable turbulence and dissipation of energy at the barrier results in a choppy and irregular standing wave system, accurate measurements of which are impossible.

It was necessary, therefore, to determine the incident wave height by some other method, and the procedure adopted was that of calibrating the crank arm of the wave machine in terms of the progressive wave heights produced. The balance was removed and an absorbing beach was constructed at the far end of the channel. Waves were then generated with a range of crank arm settings for each of the three wave periods used, which were approximately 1.00, 1.60, and 2.80 seconds, and the wave heights at the ultimate location of the barrier were recorded.

Particular wave heights observed on these calibration runs were then correlated with corresponding waves on the later force runs. In the case of the 2.8-second waves, for example, the fourth, fifth and sixth waves from start-up were found to be reasonably constant in height, and were correlated with the fourth, fifth and sixth fluctuation of the lift, thrust and moment records made at the same crank arm setting. The particular waves chosen occurred before any re-reflections from the wave machine arrived at the barrier.

## C. Experimental Results

The results of the balance measurements are shown in Figs. 2 to 4. The wave heights along the abscissa are those of the incident progressive waves. All values are simultaneous readings at the time of maximum shoreward thrust, thus the lift values are downward and the moment given is the shoreward overturning moment about the seaward toe of the barrier. Slight phase differences exist between thrust, lift and moment, but since the thrust

is the major component, the values of maximum force and maximum shoreward overturning moment will not differ greatly from the values presented.

As mentioned earlier, the above and below still-water portions of the barrier were tested both separately and together. The values of thrust given are the maximum for each part tested and do not consider any phase relationships. There exists, however, a definite phase difference between the time of maximum thrust for the top and bottom sections. For the 10.5-ft wave (1.60-second period) the maximum thrust for the above still-water portion occurs approximately  $15^{\circ}$  after the maximum for the whole barrier. The maximum thrust on the below still-water portion occurs approximately  $19^{\circ}$  ahead of the maximum for the whole structure. This phase difference between top and bottom agrees fairly well with the differences found in the pressure measurements presented in Part III. The phase difference for the 21.0-ft wave (2.80-second period) was not obtained from the balance measurements.

Considering the phase difference between top and bottom, it is expected that the sum of the magnitudes of the force components for the top and bottom portions should be something greater than the magnitude for the whole barrier. In some cases, however, this result is not obtained. This anomaly can be attributed to the inability of the experimental technique to reproduce exactly the same wave conditions for the different test runs. This discrepancy, however, does not appreciably distort the over-all results.

#### D. Discussion

It is apparent from Fig. 3 that the major portion of the thrust on the barrier occurs on the portion below the still-water level. Neglecting any phase difference between top and bottom, this amounts to 82 per cent for the 10.5-ft wave and 76 per cent for the 21.0-ft wave. This percentage is fairly constant throughout the range of the wave heights tested. There is no lift on the lower portion of the barrier and therefore the maximum thrust equals the maximum force. Since this portion is a vertical plane barrier, it is interesting to note that the theory for such a barrier agrees with the experimental results. The dashed theory curves of Figs. 3 and 4 are computed using the combined momentum theory developed in Report E-11.1, October 1953. These curves are computed for only the part below still water and use a reflection factor which was chosen to fit the experimental data. For

the 21.0-ft wave the factor is 0.85; for the 10.5-ft wave the factor is 0.80. These factors, however, appear reasonable since observation of the barrier shows some dissipation of energy in the form of turbulence and spray over the stepped portion.

The lift and thrust components of force for the above still-water portion of the barrier are nearly equal. Thus the resultant force vector acts at approximately  $45^{\circ}$  with the horizontal. Due to the relatively small magnitude of lift, it has little effect on the resultant force for the whole structure. Its effect on the moment, however, is appreciable. As can be seen from the curves (again neglecting any phase differences), the moment for the bottom portion due to the 10.5-ft wave is nearly constant at 73 per cent of the total over the range of wave heights tested. For the 21.0-ft wave the percentage extends from 73 per cent for the smaller wave heights to 58 per cent for the larger waves.



### III. PRESSURE MEASUREMENTS

#### A. Equipment

The equipment used for the measurement of pressures resulting at the stepped barrier, Case 5, is the same as was described in the Interim Report for December 1952 to March 1953, with minor exceptions. In that report it was stated that the last six feet of the one-foot wide channel consisted of 1/2-in. tempered plate glass. One of the panes failed in early October, and rather than order additional material and construct a new wall section, it was considered more practical to shorten the channel six feet. In addition, one of the four pressure transducers ceased to function properly, so that it was necessary to remove it from the system. This necessitated the discontinuation of recordings at tap No. 0 which was located 2.5 in. from the bottom.

The barrier had active pressure taps as follows: eight on 2.5-in. centers from 4.5 to 18.5 in. above the floor; four on 1-1/8-in. centers from 19-5/8 to 23 in.; one each in the centers of the 2.4-in. wide treads at 24.0, 26.4, 28.8, and 31.2 in.; and one each through the centers of the 2.4-in. high risers at 25.2, 27.6, 30.0, 32.4, and 34.8 in. above the floor. The openings, 1/8-in. diameter on the seaward face, are connected to one of the three manifolds in groups as 1, 4, 7.....; 2, 5, 8.....; 3, 6, 9....., so that one of each group was valved into the corresponding manifold at all times. Each manifold was connected to a pressure transducer. The movements of the transducer elements were recorded on the Heiland oscillograph. The transducers were calibrated once a week hydrostatically and twice daily electrically.

#### B. Technique

The experimental procedure for investigating the pressures against the barrier was the same as with the plane barriers described in Report E-11.1 except for the measurement of wave heights. Due to the shortness of the one-foot wide channel, it was not possible to install there a sloping beach in order to calibrate the wave machine in terms of the height of the progressive waves produced as was done in the channel where the total force and moment against the bulkhead were measured. This inability to

measure directly the height of the progressive wave at the barrier was not of great concern in the study of plane barriers, since in that case the heights could be obtained from the height of the standing wave.

For the offset barrier study, the only method available was that of measuring the progressive waves at a point seaward of the barrier during the short interval before reflections from the barrier reached the measuring station, and assuming these heights to be the same as the heights at the barrier. A submergence element was therefore installed 30 ft from the barrier. In a 2-ft water depth a 20-ft long wave has a celerity of 7.58 ft/sec and a period of 2.65 sec., and the corresponding values for a 10-ft long wave are 6.60 ft/sec and 1.52 sec., so that it was possible to obtain from the oscillograph records the values of the progressive wave, uninfluenced by reflections, by reading as late as the third and the fifth or sixth waves for the 20- and 10-ft long waves, respectively. Each wave length was observed in triplicate runs, and an excellent agreement for both crest heights and total wave heights was obtained.

### C. Results

The data obtained from the two sets of three runs each, which were averaged, are summarized in Figs. 5 and 6 for waves 10 ft long, 5 in. high and 20 ft long, 5-1/4 in. high, respectively. The data shown represent positive pressures against the barrier, i. e., pressures in excess of the still-water hydrostatic head. The pressure-elevation curves shown may not be integrated for the calculation of total force and moment as was the case with plane barriers (Report E-11.1) since the data points shown are individual maxima, not necessarily occurring simultaneously. The upper portion of each graph shows the phase relationship of the 18 readings. It is seen that fairly large phase differences exist, particularly with the 10-ft waves. It should, however, be emphasized that below the still-water surface, due to the rather flat peaks of the pressure-time records, the phase differences are of only slight concern and the data points in this region may well be treated as simultaneous values. Above the still-water level, the phase differences are more significant, and the values shown correlate with the total force phase differences referred to previously.

Figures 5b and 6b show also theoretical curves based on the time rate of change of the horizontal and vertical components of momentum (with values of reflection factor as specified previously) as derived in Report

E-11.1. It appears that a very good correlation exists between the theory and the experiments, with the exception of the vicinity of the still water surface where the experimental values are 43 per cent higher for the 10-ft long wave and 30 per cent in the case of the 20-ft long wave. Even with these local differences, the areas under the theoretical and experimental curves are seen to be nearly equal, which is the result obtained also from the force balance experiments.

It is interesting to note also that the pressures at the still water level and above, as determined from the experimental runs, are approximately equal for the two wave lengths, while below the still water surface the longer wave length results in much higher pressures. This suggests that the pressures on the stepped portion, where partial wave breaking occurs, is a function of wave height only, which supports the postulate that the pressures in this region of the barrier correspond to the velocity head ( $\frac{w}{2g} V^2$ ) of the jet of water striking the barrier as the result of wave breaking. The jet velocity for this special case of partial wave breaking cannot be calculated theoretically at this time, hence it is not possible to further substantiate this assumption. Future work will be directed at more complete analysis of this question.



#### IV. CONCLUSIONS

In conclusion, it may be stated that this stepped barrier, Case 5, does not differ radically from a vertical plane barrier. Comparison of the results from this study with those of plane barriers (Report E-11.1, October 1953) shows that the force-height and moment-height curves for Case 5 are slightly less in general than those for a plane barrier. This is as expected since the reflection factor is less than unity. Use of the theory for plane barriers, therefore, should give conservative results. The shape and magnitude of the pressure distribution curves also confirms the above conclusion.

Barrier designated Case 6, which is similar to Case 5, will not be tested under the present schedule of experimental runs. Case 6 differs from Case 5 in that the steps are smaller and more numerous. Instead of five steps, Case 6 has ten steps of 1.2-in. rise and tread. It is the opinion of this Laboratory that the results from Case 6 will not differ appreciably from those of the barrier presented herein.

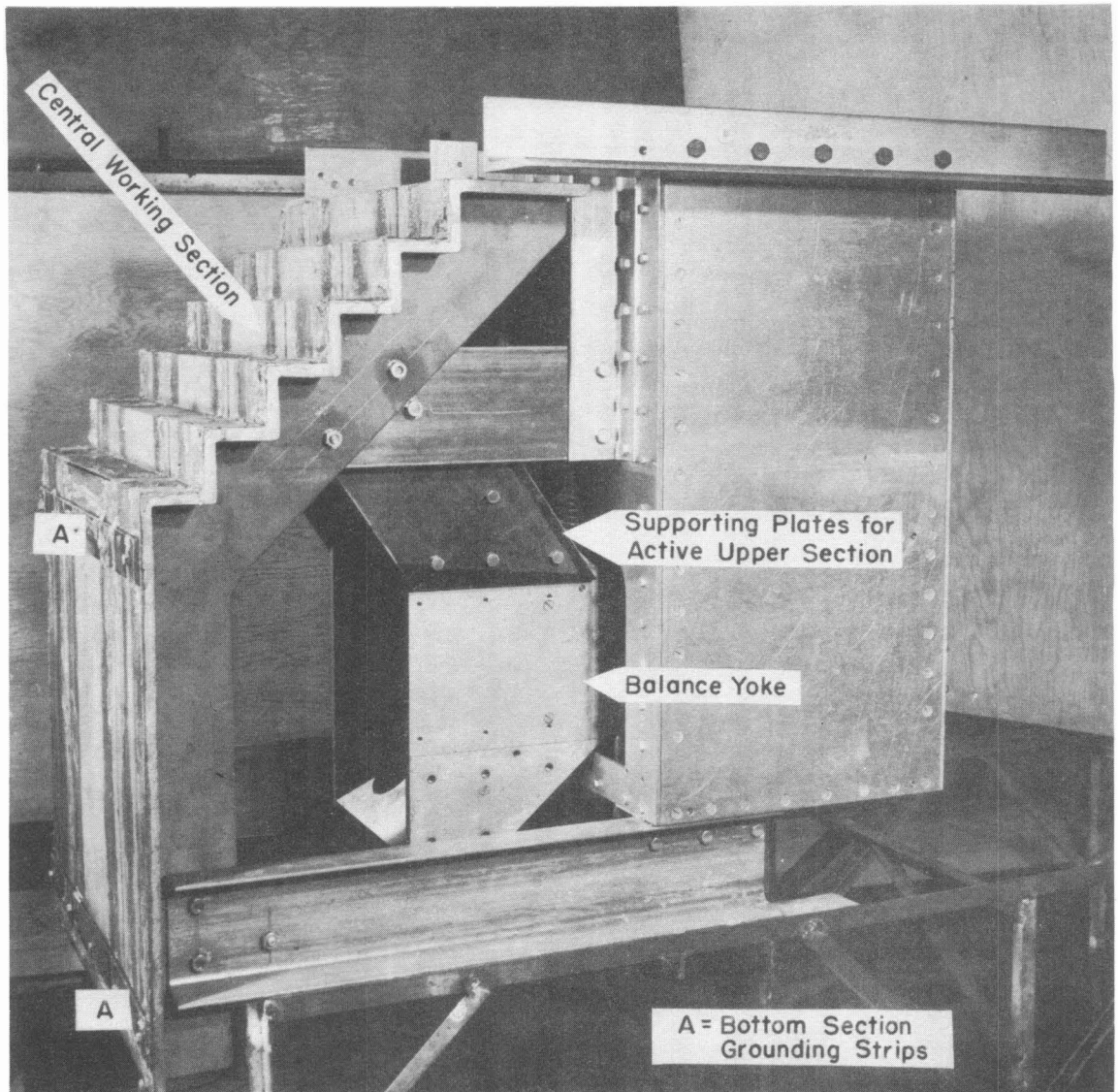


Fig. 1 - Force balance with Case 5 barrier

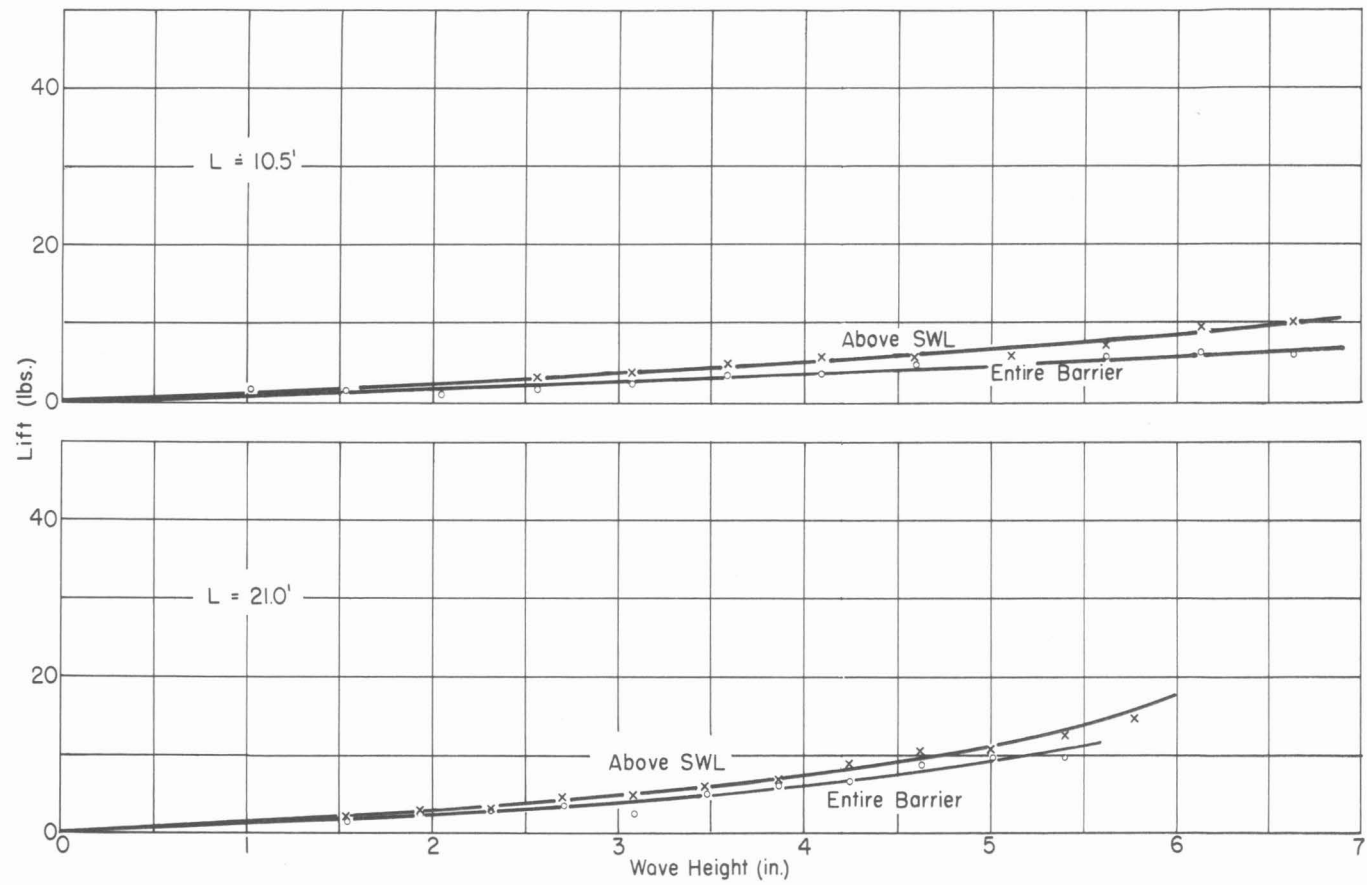


Fig. 2 - Experimental values of lift as function of wave height

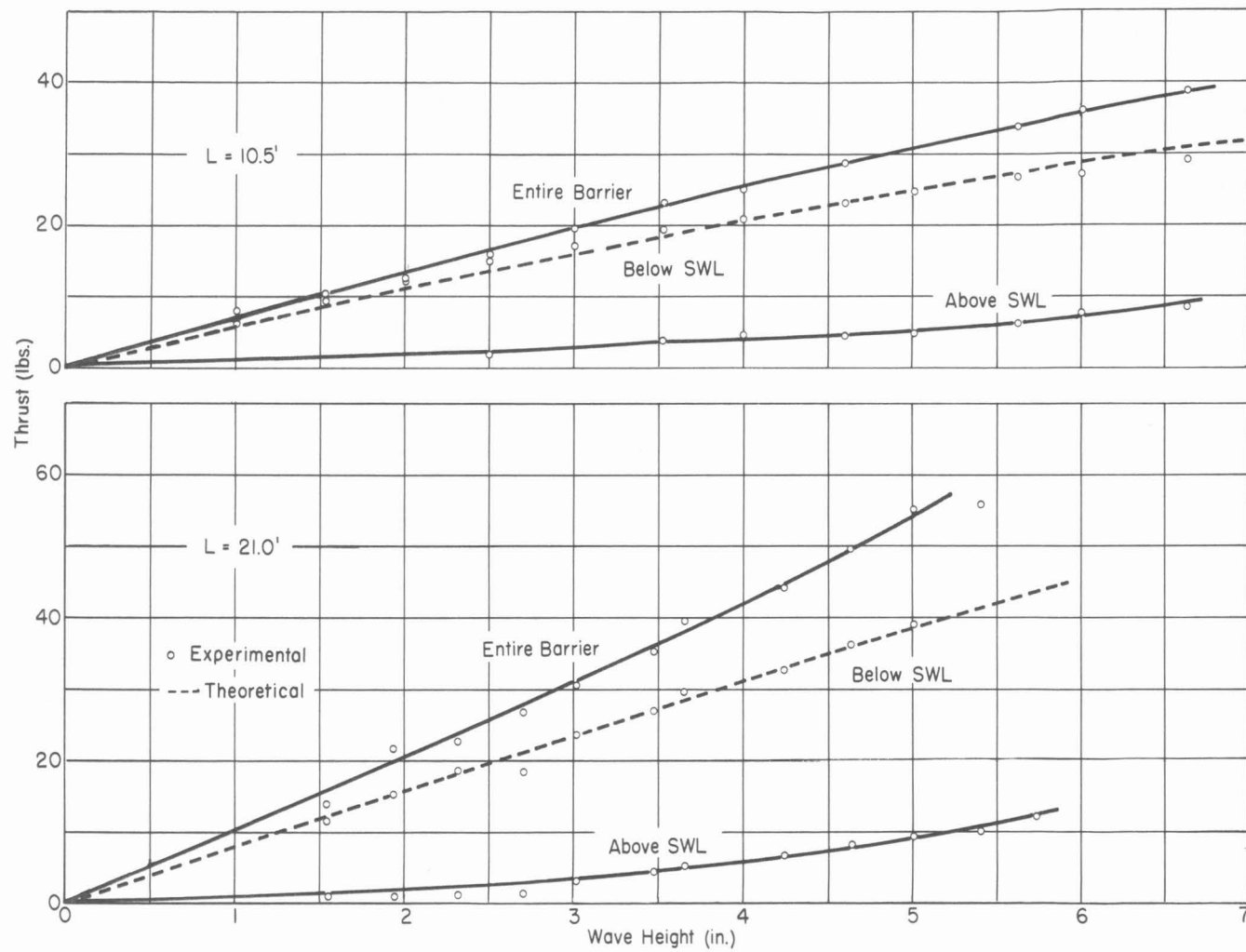


Fig. 3 - Experimental and theoretical values of thrust as functions of wave height

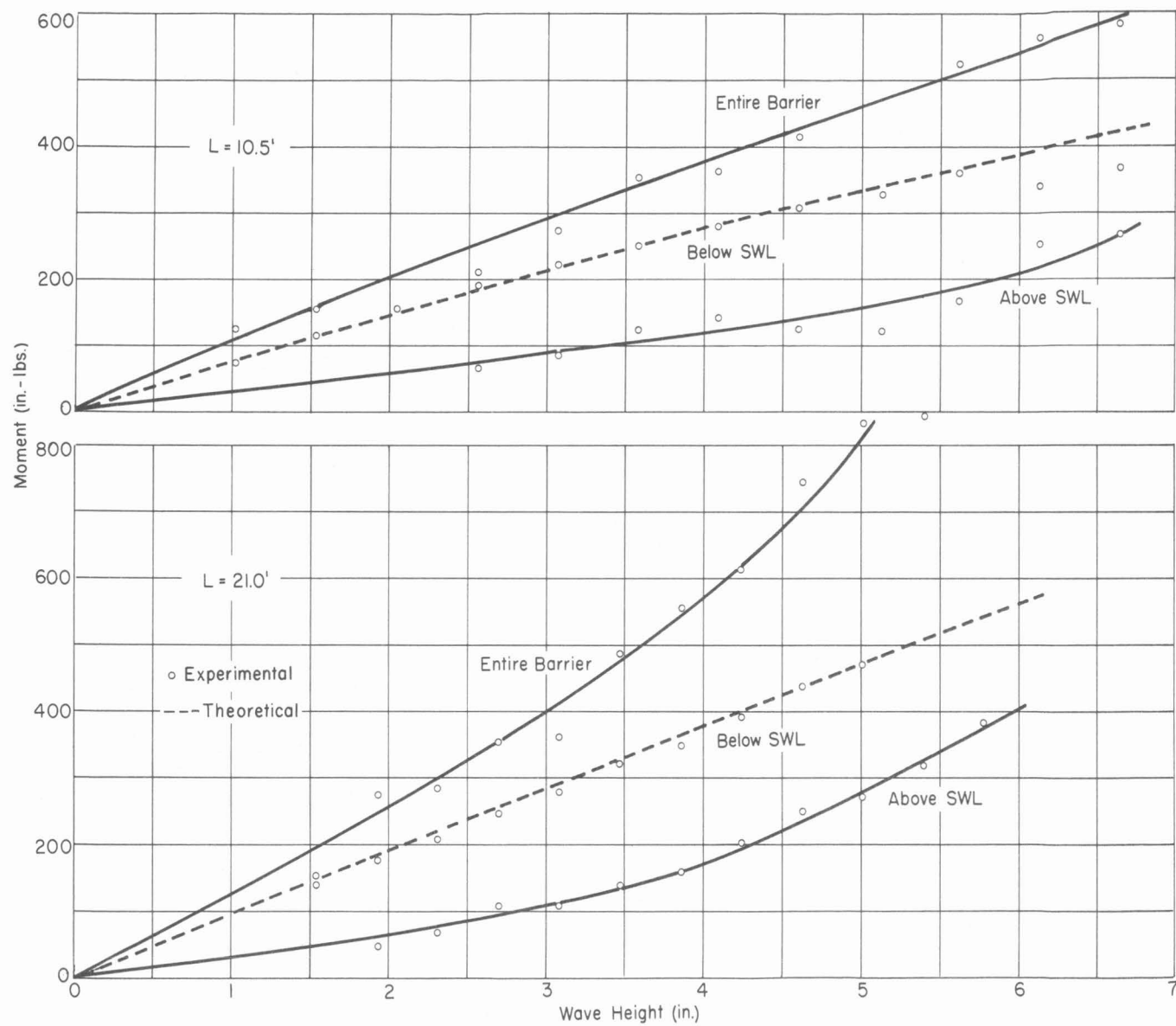


Fig. 4 - Experimental and theoretical values of moment as functions of wave height



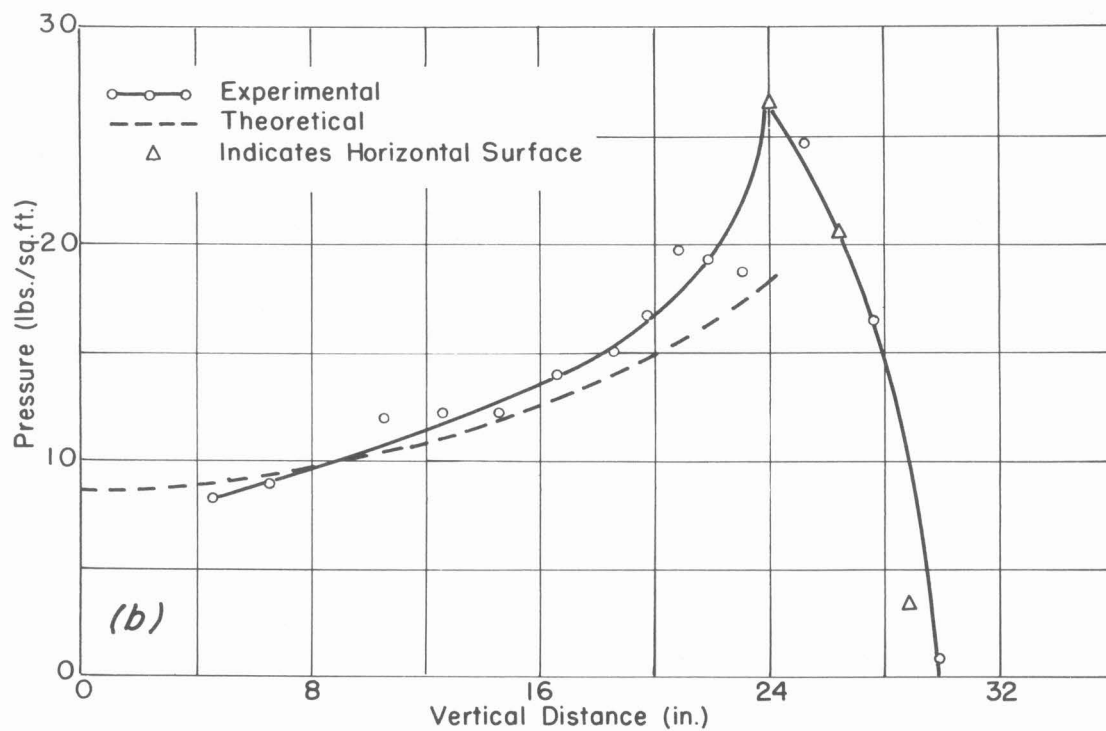
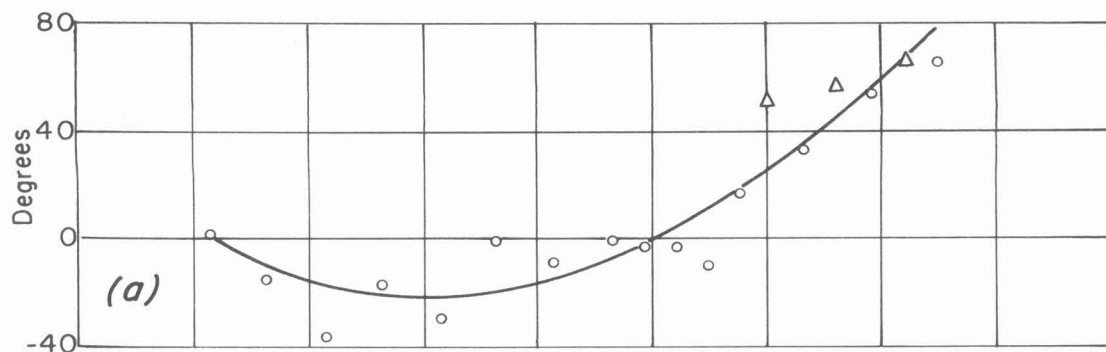


Fig. 5 - Variation of maximum pressure with position and time  
 $L = 10'$ ,  $H = 5''$

- (a) Phase relationship of pressure maxima referred to bottom pressure tap
- (b) Experimental pressure maxima and theoretical pressure distribution

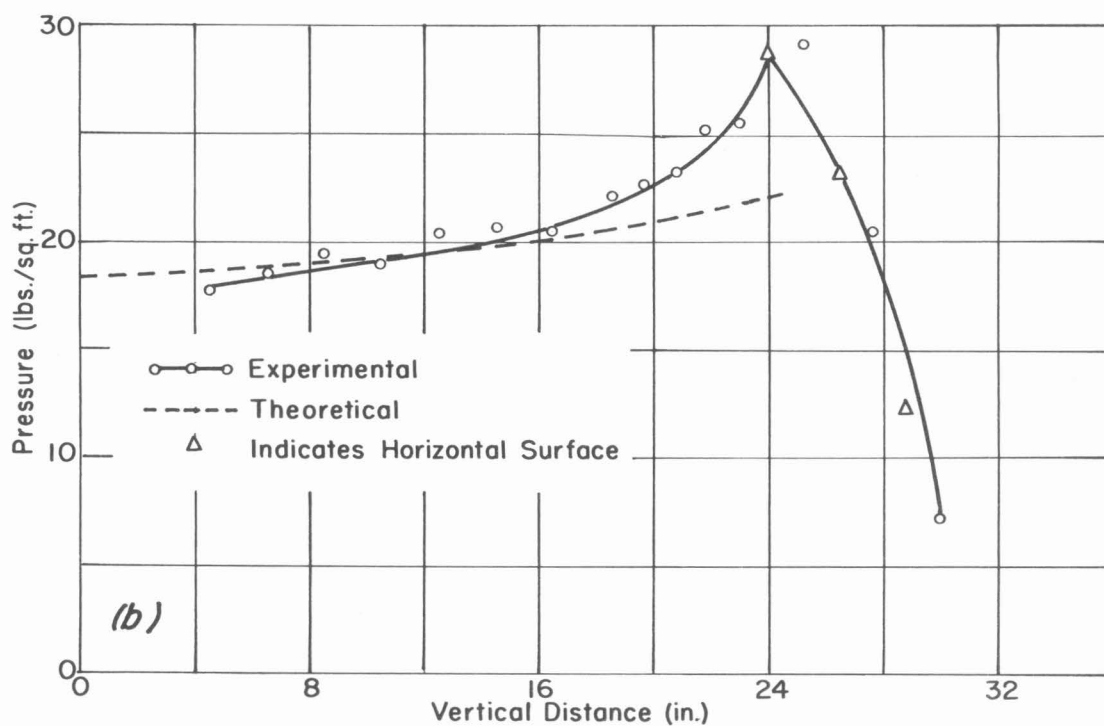
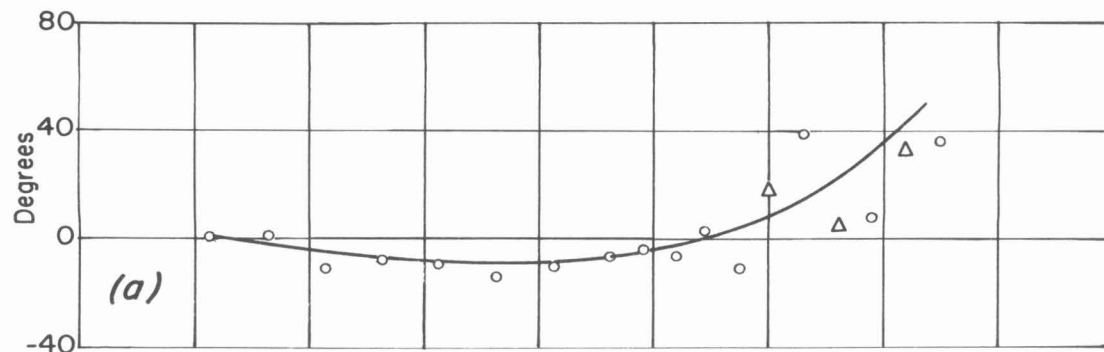


Fig. 6 - Variation of maximum pressure with position and time  
 $L = 20'$ ,  $H = 5\text{-}1/4''$

- (a) Phase relationship of pressure maxima referred to bottom pressure tap
- (b) Experimental pressure maxima and theoretical pressure distribution